MONITORING OF CORROSION PROTECTION IN REINFORCED CONCRETE STRUCTURES USING AN INTEGRATED PH OPTODE

Wolfgang R. Habel
BAM Federal Institute for Materials
Research and Testing,12205 Berlin

Ralf Röben,
Kiwa MPA Bautest GmbH,
Branch Berlin-Brandenburg, Germany

Roland Hüttl,
Kiwa MPA Bautest GmbH,
Branch Berlin-Brandenburg, Germany M.

Mathis Kuchejda
Schmidt & Haensch GmbH
13403 Berlin, Germany

Corrosion in steel-reinforced concrete structures is a critical issue. Corrosion appears if the pH value of the concrete matrix decreases due to deterioration of the calcium hydroxide layer on the steel surface. At present, several detection systems for determination of corrosion or measurement of corrosion-promotive parameters are available on the market. However, the safest information about potential danger of steel corrosion - that means, information before corrosion damages the concrete structure - is the knowledge of the pH value of concrete.

The submitted contribution presents a fiber optic pH sensor for long-term monitoring of the
pH value of reinforced concrete structures at risk from corrosion. The sensor probe is small (about 8 mm in diameter), can be embedded into the concrete matrix and observe changes in pH over years. Several sensor probes can be staggered to detect the progression of pH decrease. The pH values can be resolved with 0.1 to 0.2 pH value in the range between 12.0 and 9.5.

Extended tests have been carried out to prove the long-term stability and reproducibility in the high alkaline environment. The structure of the pH measurement system, long-term test results and some design modifications to achieve stable probes will be explained. Experience from test applications of pH sensors embedded in grouted anchors and in concrete components for a cooling tower will be presented.

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Wolfgang R. Habel[1], Ralf Röben[2], Roland Hüttl[2], Mathis Kuchejda[3]

[1]BAM Federal Institute for Materials Research and Testing, 12200 Berlin, Germany
[2]Kiwa MPA Bautest GmbH,Branch MPA Berlin-Brandenburg, 13355 Berlin, Germany
[3]Schmidt & Haensch GmbH 13403 Berlin, Germany

ABSTRACT: Corrosion in steel-reinforced concrete structures is a critical issue. Corrosion appears if the pH value of the concrete matrix decreases due to deterioration of the calcium hydroxide layer on the steel surface. The safest information about potential danger of steel corrosion is the knowledge of the pH value of concrete. The paper presents a fiber optic pH sensor for long-term monitoring of the pH value of reinforced concrete structures at risk from corrosion. The sensor probe is small (about 8 mm in diameter), can be embedded into the concrete matrix and observe changes in pH over years. Several sensor probes can be staggered to detect the progression of pH decrease. The pH values can be resolved with 0.1 to 0.2 pH value in the range between 12.0 and 9.5. The structure of the pH measurement system, long-term test results and the design to achieve stable probes will be explained. Experience from test applications of pH sensors embedded in grouted anchors and in concrete components for a cooling tower will be presented.

1 INTRODUCTION

Steel-reinforced concrete structures such as sewer pipes, cooling towers or rock anchors are often exposed to a wide variety of damaging influences. Aside from mechanical stress, corrosion of steel is one of the most relevant damaging processes in steel-reinforced concrete. It presents a safety risk to people and environment because failure can occur without prior indication. Besides moisture and chloride ions concentration, pH value is a chemical parameter of major importance for health monitoring of steel-reinforced and pre-stressed concrete structures. The lifetime of steel-reinforced concrete structures depends strongly on their pH state as embedded steels in concrete structures are only passive at pH values higher than 9. Corrosion in steel-reinforced concrete structures appears if the pH value of the concrete matrix decreases due to deterioration of the calcium hydroxide layer on the steel surface. Once the corrosion of steel components inside concrete did advance with the development of corrosion products, damage of the concrete matrix cannot be avoided yet. For this reason, long-term

monitoring of pH values in the range of 13 to 9 with a resolution of about 0.5 pH units is relevant for early detection of potential corrosion condition.

In order to get information permanently, embedded sensors should be preferred. Installation of staggered sensor probes enables to detect the distribution of pH value in a certain volume and even the progression of pH decrease. Commercially available structure-integrated sensors for early detection of steel corrosion in concrete structures do not always sufficiently match the in-situ requirements. Fiber-optic based sensors are a promising technology for corrosion monitoring because they offer a large number of attractive features such as small size, flexibility, geometric versatility, resistance in corrosive and hazardous environments, no signal interference due to present moisture, in-situ and non-destructive measurement, and immunity against lightning strokes.

At present, several fiber-optic systems for detection of corrosion or measurement of corrosion-promotive parameters are proposed, e. g. by Inaudi (2009) and Leung (2009). However, the safest information about potential danger of steel corrosion - that means, information before corrosion damages the concrete structure - is the knowledge of the pH value of concrete. In order to draw benefit from this methodology, a concrete-embeddable long-term stable fiber-optic pH sensor was developed. The most challenging requirements concern its long-term stability under strong alkaline conditions within the pH range between 13 and 9 over a period of at least 25 years. The sensor has to be integrated in harsh environments and inaccessible places. It must be guaranteed that the sensing element has an intimate contact with the concrete matrix to pick up pH change. And finally, the price of pH sensors has to be as low as possible to enable the fabrication of multiple-sensor structures.

2 DESIGN OF THE PH OPTODE

The new fiber-optic pH sensor consists of a pH-sensitive layer made of a pH indicator immobilized in a solid substrate which changes the color depending on pH values. As a result of intense investigations, the absorption method is preferred because only this method provides reliable measurement results. In order to overcome instability problems resulting from decrease of the indicator concentration due to photodegradation or leaching out, drifts of the light source intensity or bending of optical fibers, a ratiometric method based on the use of ratio between the intensities at two different wavelengths (e.g. at the intensity maximum points or at the isosbestic point) is applied. Such a ratio of intensities is not altered by external factors. The measurement principle and some more details were described by Dantan (2005) and Dantan (2006). Fig. 1 shows the measurement principle for fiber optic pH measurement and the exploded view of the sensor head; Figure 2 shows the design of the sensor head.

The diameter of the head is 8 mm; the head is pluggable and can be replaced, and the color of the sensitive membrane varies depending on pH values. The sensitive layer is protected but sufficiently sensitive for the contact with the concrete matrix. The sensitive membrane must not exceed a definite thickness because the ion diffusion is hindered. In order to ensure a reliably stable thickness of the sensitive membrane, a special powder compacting tool for manufacture of pH-sensitive membranes is developed. The measurement resolution of the sensor for pH values between 9 and 12 is in the range of 0.1 to 0.6 pH units depending on the pH values. The highest resolution can be achieved in the middle of the measurement range (between 9.7 and 11). One particular condition by now is that the pH sensitive membrane must not dry out. This

requirement is mostly fulfilled in hydraulic engineering and geotechnique. In order to prevent drying out before integration into concrete structures, the pH sensitive membrane is protected by a small watertight topcoat (Fig. 4).

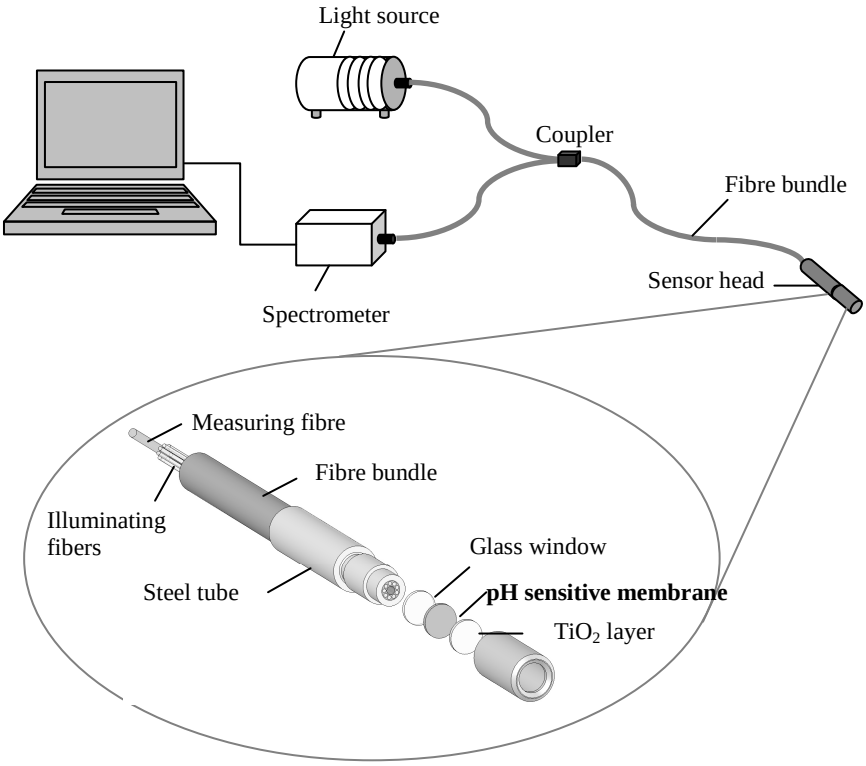

Figure 1. Measurement principle and exploded view of the sensor head.

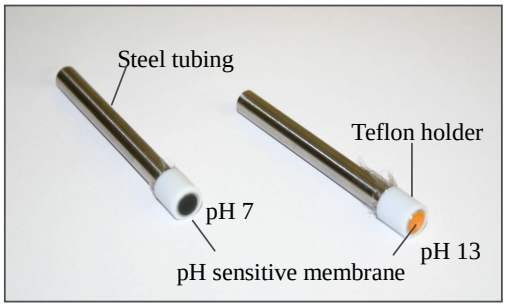

Figure 2. pH sensor head design.

Figure 4. Sensor head shortly before installation.

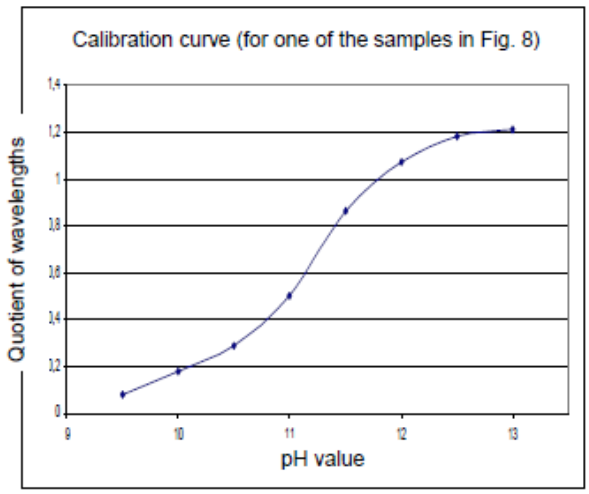

Figure 3. Calibration curve of one of the samples

prefabricated for installation in the cooling tower

(see Figs. 7 and 8))

3 FIRST FIELD TESTS

Suitability of this sensor was successfully tested first in steel anchors installed in the harbor of Rostock (North Germany) in summer 2010. Figure 5 shows two of totally 10 pH sensor prototypes that were fixed on prefabricated anchor bodies (two in each anchor) before introducing them into the borehole. The topcoat (Fig. 4) was removed shortly before introducing the anchor into the borehole and grouting. This procedure ensured that the membrane maintained its hydrophilic properties. The sensors provided useful information about the pH values of the grout.

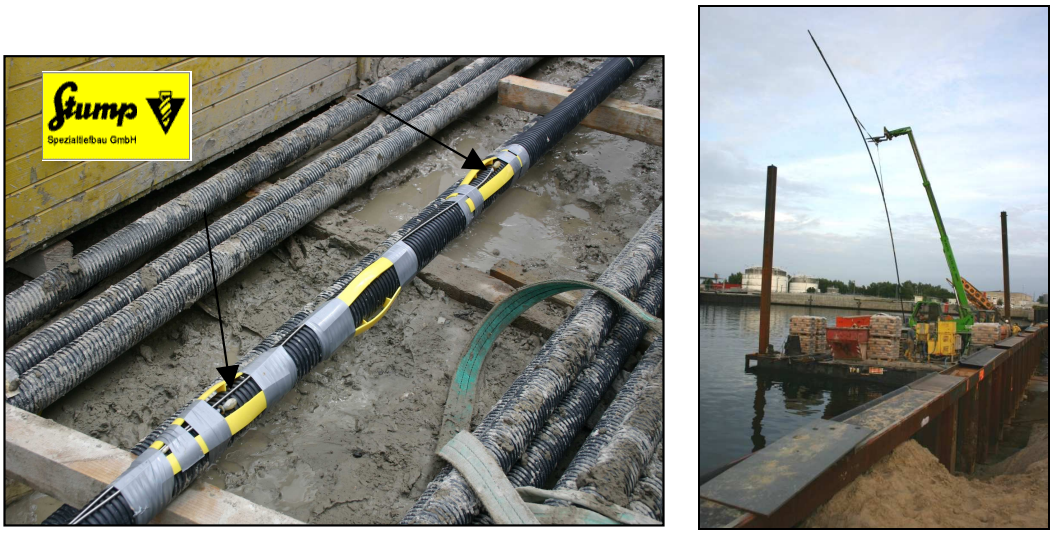

Figure 5. Prefabricated anchors with fixed pH sensors (left picture, arrows). Having fixed the sensors, the anchor was installed in the drill hole (picture right).

4 OPTIMISATION OF THE SENSOR SYSTEM

The long-term function of the concrete embeddable pH sensor could be proved by a series of investigations carried out over the last 6 years. It could be observed that the most serious attacks concerning stability of pH-sensitive membrane occurred in the first few months. The sensor concept has been optimized for commercial use and is being installed in cooling towers of a power plant.

Figure 6. Mortar samples with pH sensors (left); acid bath for simulation of chemical attack (right).

The sensor concept has been prepared for commercial supply. Relating to his, special attention was put on optimization of the robustness of sensor elements and integration technology. Moreover, a series of investigations have been carried out to clarify whether the membranes are capable of recording pH changes in concrete structures appropriately. For this purpose, several sensor heads were embedded in fresh mortar test prisms (Fig. 6, left) according to the standard protocol DIN EN 196-1. After a one-month curing period in water, the mortar samples with integrated sensor heads have been stored in an acid bath for simulating environmental attack and thus pH decrease under real harsh conditions (Fig 6, right). From this moment the sensor signal has been monitored at regular time intervals and has showed expected pH changes of the concrete matrix. Using these mortar samples, microscopic studies will be performed in the coming months to confirm the intimate contact between the sensitive membrane and the concrete matrix.

5 USE OF PH OPTODES FOR MONITORING OF A COOLING TOWER

A new coal-fired power plant with 750 MW power is being constructed in Lünen in the German state North Rhine Westphalia and will be completed in 2012. The most remarkable building of the power area is a cooling tower with a height of 160 m**.** It is a natural ventilation cooling tower and needed for condensation of the water heated up during combustion. Because of the combustion products like sulphur dioxide or nitrogen oxides, there is a weak acid environment. Despite this acid environment, the tower shell does not get a protective layer on the inside. Such environmental conditions inside the cooling tower require a highly durable concrete with an integrated monitoring system which allows to detect concrete corrosion due to acid attack. Therefore, pH optodes are to be installed to monitor the pH value of the concrete shell. In case of a critical decrease of the concrete's pH value, measures for protecting the concrete matrix and the steel reinforcement can be implemented on time. Figure 7 shows the building site in Lünen and the cooling tower design.

Figure 7. Coal-fired power plant in Lünen, Germany

(Photos: Information sheet „Energie für morgen“ Trianel GmbH, http://www.trianel-luenen.de/)

The pH optodes are embedded in concrete bodies that are placed near the top of the tower in the vapor area of the condensed water. In this area commonly occurs the most serious attack.

The concrete sensor cubes with edge length of 15 cm were manufactured on-site using the real cooling tower's concrete. In every cube, three pH optodes were embedded whereas the sensitive membranes were covered with different thicknesses of concrete: 5 mm, 10 mm und 15 mm. Figure 8 shows an instrumented concrete cube; at the upper side, the three sensor shafts can be seen. The optical fiber for connection of the sensor probes is inserted into these shafts.

Figure 8. Concrete cube with three embedded fiber-optic pH sensors. The concrete coverage (at bottom side) is 5 mm, 10 mm und 15 mm.

The instrumented concrete cubes will be installed shortly before commissioning of the cooling tower. The pH values will then periodically recorded. Figure 9 shows the pH response (Quotient of wavelengths 605 nm and 495 nm) of one cube beginning with concreting. The ordinate value of 1.2 corresponds to a pH value >12.5, the ordinate value of 0.1 a pH value of <9.7. All sensors aged 7 weeks and older provided identical responses.

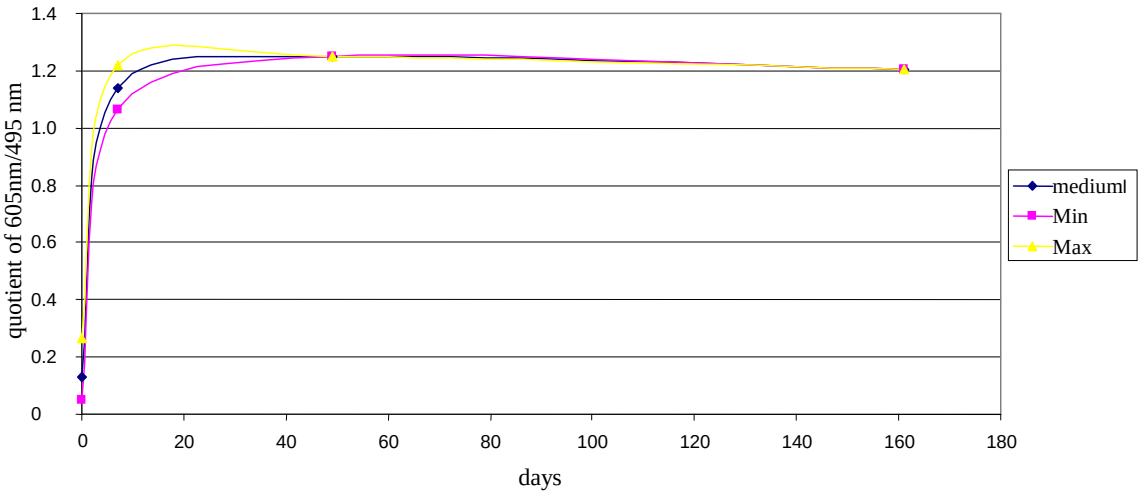

Figure 9. Wavelength response of pH sensors in concrete cube after concreting.

6 CONCLUSIONS AND OUTLOOK

Field trials over 6 years revealed that the operating principle of the fiber-optic pH sensor is suitable for integration in building materials and does not show ageing effects. With regard to a broad economical commercial use, the design was optimized based on experience from test field application. This optimization procedure enables now to install such pH optodes in numerous application areas such as in reinforced and pre-stressed concrete structures as well as in ground engineering. However, universal application of this sensor concept is not yet possible, since the sensor membrane must not dry out during construction or operation. The use of this sensor should be focused on areas of application where the cement-bound building material remains adequately moist, such as foundations for hydraulic engineering applications (offshore-wind energy converters, docks, dams) and waste water facilities (waste water pipes, main sewers, settling tanks). Particularly for the latter application there is significant demand for corrosion monitoring sensors, in order to reduce the high costs resulting from corrosion damage.

7 ACKNOWLEDGEMENTS

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